# Advances in Robotic Servicing Technology Development

Gardell G. Gefke[*]
*Vehicle Systems Integration, LLC, College Park, MD, 20740*

Alex Janas[†]
*Stinger Ghaffarian Technologies, Inc., Greenbelt, MD 20770*

Joseph Pellegrino[‡] and Matthew Sammons[§]
*Orbital ATK, Beltsville, MD 20705*

*and*

Benjamin Reed[**]
*NASA/Goddard Space Flight Center, Greenbelt, MD 20771*

**NASA's Satellite Servicing Capabilities Office (SSCO) has matured robotic and automation technologies applicable to in-space robotic servicing and robotic exploration over the last six years. This paper presents the progress of technology development activities at the Goddard Space Flight Center Servicing Technology Center and on the ISS, with an emphasis on those occurring in the past year. Highlighted advancements are design reference mission analysis for servicing in low Earth orbit (LEO) and asteroid redirection; delivery of the engineering development unit of the NASA Servicing Arm; an update on International Space Station Robotic Refueling Mission; and status of a comprehensive ground-based space robot technology demonstration expanding in-space robotic servicing capabilities beginning fall 2015.**

## Nomenclature

ARM    = Asteroid Redirect Mission
ARCM   = Asteroid Redirect Crew Mission
ARRM   = Asteroid Redirect Robotic Mission
ARV    = Asteroid Redirect Vehicle
DRM    = Design reference mission
DRO    = Distant retrograde orbit
EDU    = Engineering development unit
EVA    = Extravehicular activity
FDV    = Fill and drain valve
GEO    = Geostationary Earth Orbit
GSFC   = Goddard Space Flight Center

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[*] Chief Robotic Systems Engineer, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.
[†] Robotics Systems Engineer, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771.
[‡] Design Reference Mission Manager, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.
[§] Systems Engineer, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member
[**] Deputy Project Manager, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.

ISS       =   International Space Station
LED       =   Light emiting diode
LEO       =   Low Earth orbit
Restore-G =   Restore-GEO
Restore-L =   Restore-LEO
RFI       =   Request for Information
RRM       =   Robotic Refueling Mission
RSV       =   Restore Service Vehicle
SSCO      =   Satellite Servicing Capabilities Office
VIPIR     =   Visual Inspection Poseable Invertebrate Robot

# I.  Introduction

NASA's Satellite Servicing Capabilities Office (SSCO) has matured robotic and automation technologies applicable to in-space robotic servicing and robotic exploration over the last six years.  Initial research efforts focused on servicing existing satellite assets in geostationary orbit. On-orbit flight development testing, with International Space Station (ISS) robot platforms and Goddard Space Flight Center (GSFC) robot-compatible tools and technologies, has been conducted since 2011, with future ISS activities planned. Through ground-based experiments and these in-orbit demonstrations, the SSCO has demonstrated an array of automation and robotic capabilities and technologies needed for multiple missions, all which are aligned with NASA's long-term strategy. These missions include, but are not limited to: satellite servicing in both low Earth and geostationary orbits; the support of human exploration beyond Earth orbit; low gravity field activity such as on asteroids and small moons; planetary surface tasks; maintenance of human exploration spacecraft; assembly and servicing of a large space telescope; and an asteroid redirect mission.

This paper presents the progress of technology development activities at the GSFC Servicing Technology Center and supporting facilities, and also on the ISS, with an emphasis on those occurring during the last year.

# II.  Design Reference Missions

## A.  Design Reference Missions Overview

Since 2009, SSCO has been studying and developing multiple design reference missions (DRMs) to generate and guide the development of technologies necessary for satellite servicing. To foster the maturation of these DRMs and the associated technologies, SSCO has investigated public-private partnership over the years by releasing Requests for Information (RFI), hosting international workshops, and holding requirement reviews. Initially, SSCO studied a notional satellite servicer that would service space assets in geosynchronous orbit (GEO), extending the life of these assets via on-orbit refueling. Later DRM studies involved a notional low Earth orbit (LEO) government asset as the client vehicle. SSCO's servicing technologies also play key roles in NASA's proposed Asteroid Redirect Mission (ARM). SSCO is the lead for the robotic capture system, which will utilize prime elements from the servicing technology portfolio.

## B.  Satellite Servicing – GEO and LEO

*1.  History*

SSCO has studied missions to service satellites in both GEO and LEO orbits since its inception in 2009.  The first DRM aimed to refuel
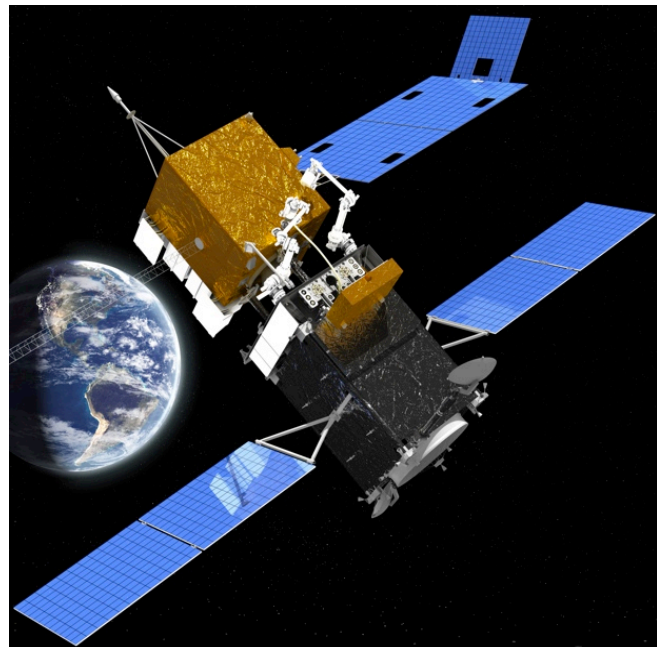


**Figure 1.  Notional Restore Service Vehicle (right) servicing a Client Spacecraft.**

a government asset at GEO orbit followed by multiple commercial clients. The mission, named Restore-G, uses a Restore Servicing Vehicle (RSV) consisting of the Servicing Payload (SP) and a spacecraft bus. A Systems Engineering Review was held in August 2012 and a SP System Requirements Review in March 2013. RFIs for Restore-G and necessary technologies were released in 2009, 2011, and 2013.

A LEO DRM study, Restore-L, began in early 2014 and leveraged the large body of work from the Restore-G study. The notional Restore-L mission utilizes an RSV to refuel a Government-owned LEO satellite approaching a fuel-exhaustion end of life. Subsequently, SSCO has released two Requests for Quotes (RFQs) to study a Restore-L mission with potential bus providers. To date, Restore-L is mentioned as part of NASA's RFI for the ARM mission, seeking synergistic opportunities between the ARM mission and Restore-L Spacecraft Bus.[1] A notional image of RSV servicing a client is seen in Figure 1.

Missions such as Restore-G and Restore-L have the potential to extend the operational lifetime of satellites, improving return on investment for government and commercial stakeholders, thereby delivering significant savings and/or gap mitigation.

### C.  Robotic Servicing Technologies in the Servicing Payload

The RSV was specifically designed to be able to service non-cooperative clients – satellites that were not designed for servicing – via advanced technologies. To service these non-cooperative clients, the RSV uses a robotic arm for autonomous and teleoperated servicing tasks. For instance, the RSV uses robotic arms that use machine vision technology and an advanced gripper tool to autonomously grapple the client, securing the client to the RSV. Ground testing this capability is shown below in Figure 2.

Once the client is berthed, the robotic arms are teleoperated to gain access to the client's fill and drain valve (FDV), where the refueling interface is located. To gain access, the robotic arms must first cut and manipulate multilayer insulation (MLI), cut safety wires and remove  two types of caps, all via a suite of advanced tools. These tasks require fine dexterity and control of the robotic arms and tools. See Figure 3.

When the client FDV is accessible, the robotic arm is teleoperated to mate the Refueling Tool to the FDV so that the client can be refueled.  Secure mating to the client FDV ensures that propellant can be transferred from the RSV to the client to replenish the client's propellant load. These technologies and techniques are consistently being developed and tested at SSCO. Space-based endeavors such as the Robotic Refueling Mission (RRM) module currently on ISS complement ground-based efforts. See Figure 4.

These tasks, from grasping and handling a multi-ton satellite to manipulating relatively small fueling caps and wires, set the wide range of capability required of the robotic arm and tool technology.
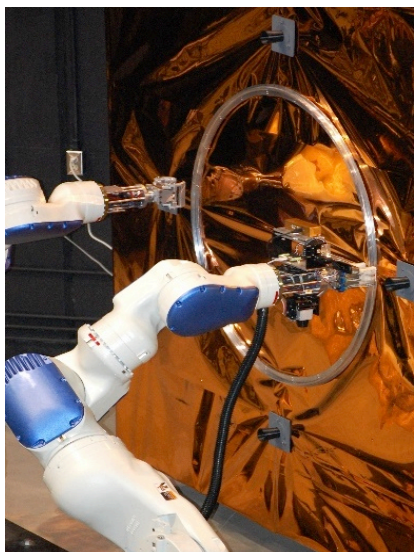


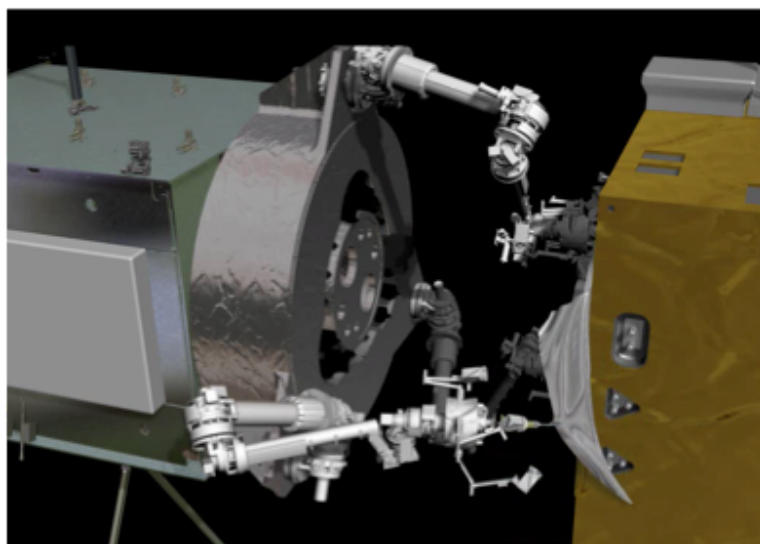**Figure 2. Robot arm ground testing of autonomously grasping a client satellite**



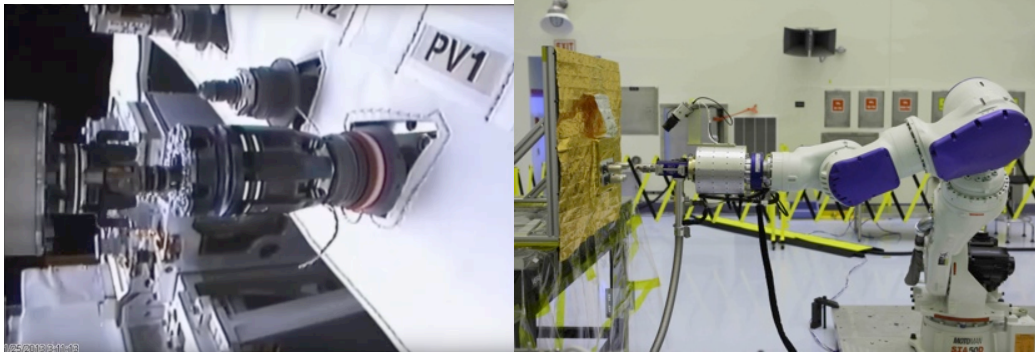**Figure 3. Notional RSV Servicing a Client Satellite**

**Figure 4. Refueling on RRM (left) versus ground testing (right).**

### D. Asteroid Redirect Robotic Mission

The robotic arm technology also supports NASA's Asteroid Redirect Mission (ARM). Within the ARM mission architecture, the Asteroid Redirect Robotic Mission (ARRM) uses the NASA Servicing Arms and associated technologies to acquire an asteroid from the surface of a larger asteroid. The Asteroid Redirect Vehicle (ARV) contacts the surface of an asteroid and uses the dexterous servicing arms, tool drives, and special gripper to acquire and retain the asteroid. See Figures 5 and 6.

After asteroid retrieval, the ARRM vehicle would transfer it to lunar distant retrograde orbit (DRO). Once in lunar DRO, the Asteroid Redirect Crewed Mission (ARCM) would perform extravehicular activities, with the assistance of the robotic arms, to gather asteroid material samples.[2]

NASA's Restore-L mission and the ARRM both incorporate the use of key robotic servicing technologies in development at NASA SSCO. There exists large synergy in the robotic technology development required for both missions, and SSCO is pursuing activities to mature these necessary technologies.

## III. NASA Servicing Arm Engineering Development Unit

Since 2009, NASA has been developing the NASA Servicing Arm, a 2-meter class, seven-degree of freedom robot arm that can be used on missions as diverse as on-orbit satellite servicing, asteroid capture, and the assembly and servicing of large telescopes in space.

The Servicing Arm has extensive heritage



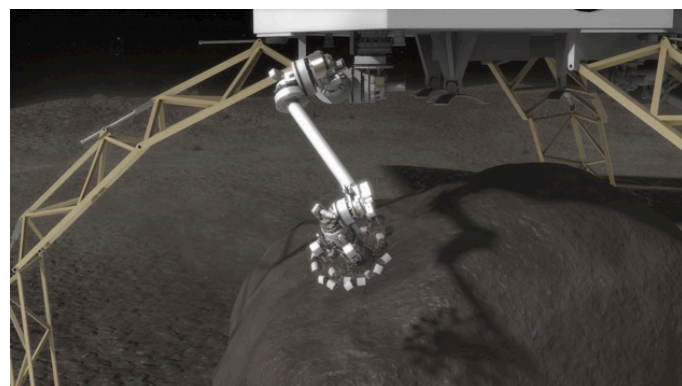**Figure 5. ARRM uses robot technology to retrieve an asteroid from a larger asteroid.**



**Figure 6. NASA Servicing Arm on ARRM vehicle retrieving asteroid.**

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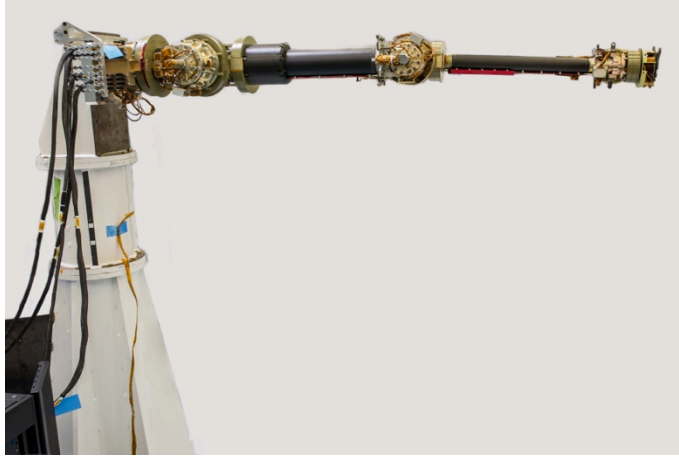American Institute of Aeronautics and Astronautics

**Figure 7. NASA Servicing Arm EDU on Pedestal.**

from arms used in past Mars rover missions. The system design heavily leverages the flight-qualified robotic arm developed for the Defense Advanced Research Projects Agency's (DARPA) Spacecraft for the Universal Modification of Orbits and the Front-end Robotics Enabling Near-term Demonstration (FREND) programs in the mid 2000s. In particular, it builds off of previous NASA and DARPA investments in motion control, robotic software frameworks, flex harnesses, force-torque sensor, joint design, and flight operations experience.

In June, the SSCO received the first engineering development unit (EDU) of the NASA Servicing Arm system. This unit was developed by MDA US Systems and Motiv Space Systems, with additional in-house development performed at NASA GSFC. The EDU arm is a full-scale system with flight form and function to support all the potential in-space robotic applications described in this paper.

The 2 meter class arm includes the EDU Advanced Tool Drive System. In 1-g, it can operate with a tool or other end effector payload and still exert all planned trajectories, forces and torques for the following design reference missions: Restore-G, Restore-L and ARRM. The force and torque levels can be achieved throughout the arm's nearly spherical work volume. For asteroid retrieval scenarios, minor modifications can increase the extraction force capability.

This servicing arm can perform in both 1-g and 0-g, the high accuracy, high speed maneuvers with fine force and torque control necessary to manipulate MLI, small fuel caps and safety wire on FDVs, electrical connector covers and satellite fasteners. For mission planning, a top tool tip speed sufficient for autonomous grasp of client satellites and a high rate control loop allows the arm to achieve compliance control even with high environmental stiffness for delicate contact force control on worksite interfaces. Contact force can reliably be maintained using feedback from the arm's force torque sensor that is proximal to the tool drive, i.e. between robot arm wrist and tool drive.

In 0-g, the arm can position very large masses with sub-centimeter accuracy relative to the serving or exploration spacecraft. This includes maneuvering a potential client spacecraft with a single NASA Servicing Arm and an asteroid with two NASA Servicing Arms.

## A. Development Challenges Faced

Retaining the ability to perform servicing and asteroid contact tasks in 1-g allows the robot subsystems developed with this arm to undergo extensive, repetitive, full-motion ground testing to ensure the many overlapping software control, monitoring, and hazard control applications are sequencing and functioning properly. This greatly lowers the reliance on models or highly constrained ground test setups to verify system performance, and provides greater software flexibility deeper into a mission's life cycle. It also means the robot arm is very adaptable to new mission concepts, new tools, and other arm payloads. The 1-g capability is a critical confidence builder to convince potential clients the system will perform as advertised.

## B. Robot Arm Control

The NASA Servicing Arm is controlled in two main ways. The first is in a full autonomous mode when communication time delays preclude human-in-the-loop commands or decisions points. The second is teleoperations with a spectrum of the level of human-in-the-loop commanding used.

### 1. Full Autonomous Operation

Two examples of autonomous arm control are satellite grasp ("autograsp") and asteroid extraction and retrieval from low gravity asteroids or small moons. For autograsp where expected time delays are six to ten second or more, visual feature tracking algorithms refine the robot's pose and gripper trajectory relative to the client's grasp feature, such as the client's launch Marman ring. For up to two minutes after a ground issued, "Go," the robot subsystem can autonomously maneuver the gripper tool onto the grasp feature and then maintain gripper position on the feature

while grasp is secured. When the client is securely grasped, the arm then nulls out any residual relative velocity between servicer spacecraft and client spacecraft.

For asteroid retrieval scenarios, time delays are greater than fifteen minutes, so autonomous arm actions include sequences of up to 45 minutes or more. This includes prepositioning the arm(s) prior to descent, maneuvering a gripper on to the surface, maintaining gripper position and contact force until gripper and/or a drill/anchor are fully secured on the asteroid, and finally repositioning it with respect to the spacecraft prior to contact leg push off from the larger asteroid or small moon surface.

*2. Teleoperations*

Teleoperations span the gamut from fulltime human joystick control to step commands to fully uploaded supervised command sequences. Because autonomous control requires both high on-board computing resources and a much more extensive ground test and verification program, autonomy is used sparingly and only when absolutely needed. Allowing for joystick control, while slightly more risky than scripted or sequenced motion, provides a great deal of flexibility and very timely ability to respond to contingency or off nominal situations. Enormous ground-based computing resources can be used in concert with joystick control at fairly low overall cost to increase safety and assurance of joystick operations.

With on-board path planning applications, the arm can be ground commanded in macro steps either singly or as a string of widely spaced path points. This reduces operator and supervisor workloads with little increase in risk. Another extreme is uploading tables of tightly spaced Cartesian or multi-joint maneuvers when the exact geometric path of the entire arm needs to be specified throughout a maneuver from end to end.

## IV. Robotic Refueling Mission

The Robotic Refueling Mission (RRM) is an ongoing, multiphased International Space Station payload designed to test and mature the tools and technologies associated with robotic servicing. RRM is a 1.1 m x 1.1 m x 0.8 m module consisting of four robotic servicing tools, several tool adapters, a fluid (ethanol) transfer system, and multiple task boards, valves, and spacecraft blanketing representative of those found on existing satellites. The SSCO tools contained within RRM are actuated and controlled via the Canadian Space Agency's Special Purpose Dexterous Manipulator (SPDM). SPDM control is performed at ISS mission control with SSCO personnel supporting on-orbit operations remotely from Goddard Space Flight Center. The primary control method is remote high-level teleoperation with local closed loop force-moment accommodation.

The RRM module was launched in 2011 onboard the last Space Shuttle mission, STS-135. The primary goal of this mission was to robotically transfer ethanol, a simulated spacecraft propellant, via a legacy satellite FDVs. This was demonstrated successfully in January 2013.[3]

RRM Phase 2 (RRM2), with two RRM compatible taskboards, an additional robotic tool, and five new tool adapters, launched in two shipments in 2013 and 2014. RRM2 focuses on preparing a simulated worksite for on-orbit cryogen transfer, mating electrical connectors, evaluating material samples, performing worksite close and midrange visual inspections, and evaluating fiducial marking for worksite position estimation. The robotic tooling and task boards of RRM2 were transferred and installed onto the RRM module in May 2015, and subsequent operations anticipated later in 2015.
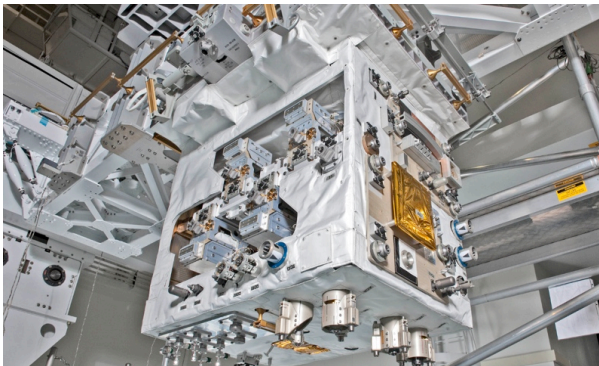


**Figure 8. Robotic Refueling Mission payload.** *During final preparations for launch, the RRM payload installed on the carrier that would take it to orbit in the Space Shuttle Atlantis cargo bay.*
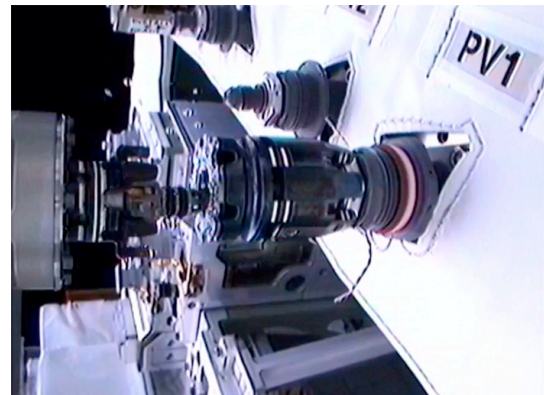


**Figure 9. Refueling tool demaiting from RRM payload after succesful ethanol transfer demonstration.** *A portion of the tool is left behind to serve as an additional seal and for easy reaccess.*
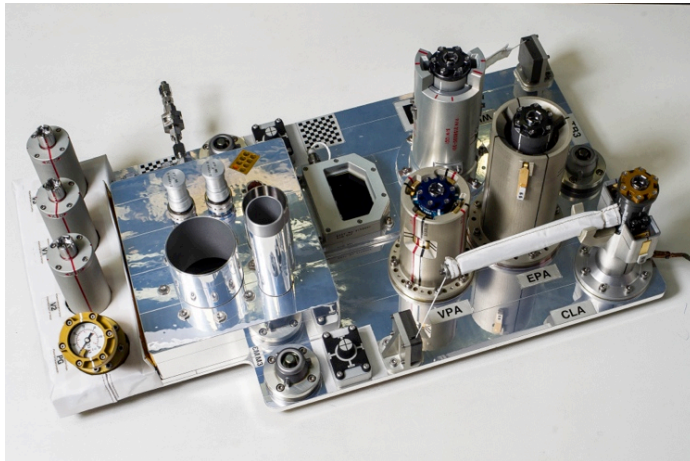
**Figure 10. RRM2 taskboard, for demonstration of procedures leading up to cryogen transfer.**

The cryogen transfer preparation procedures portion of RRM2 includes demonstrations of both sealing simulated spacecraft vents and performing a nitrogen pressure leak test. The next RRM Phase 3 (RRM3) module will demonstrate the physical cryogen transfer on legacy interfaces and is currently in the mission planning phase and tentatively scheduled for a 2017 launch. The robotic challenges associated with this task include working with legacy interfaces neither designed for use on-orbit, nor designed for robot accessibility.

RRM2 will demonstrate robotic electrical mating and continuity checks via two legacy satellite interfaces; SubMiniature version A (SMA), and common circular connectors. Visual continuity checks will be performed via solar powered LED arrays located next to each of the interfaces. The robotic challenges associated with this task are the risk of damaging fragile electrical connector pins when mating, as well as mating to an existing uncooperative interface, not designed for robotic compatibility.

Worksite inspection is a critical component to on-orbit servicing that is often overlooked. Many existing assets were launched without detailed closeout photos. As a result, thorough inspection of the client spacecraft will be required prior to, during, and post servicing operations. RRM2 demonstrated the Visual Inspection Poseable Invertebrate Robot (VIPIR) robotic tool consisting of an 8-24mm optical motorized zoom lens and the smallest camera ever flown in space by NASA, a 1.2mm camera mounted on the end of an extendable articulating hose. The 224 x 224 pixel VIPIR miniature camera was extended into a tube interface pictured below during on-orbit commanding in May of 2015. The visual inspection component of RRM2, while not difficult robotically, is a demonstration of extraordinary mechanical and electrical design and packaging.
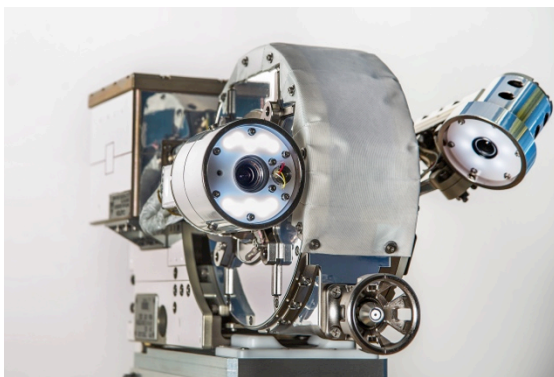
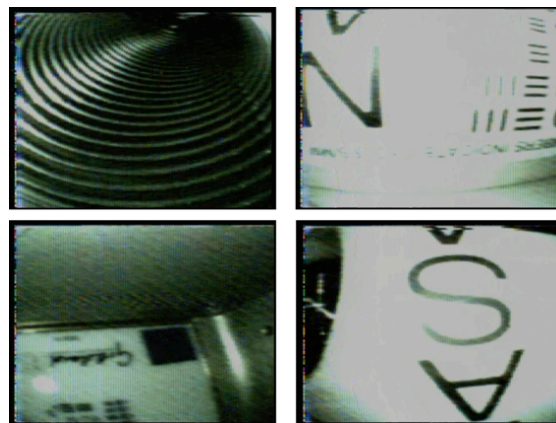

**Figure 11. VIPIR inspection tool.**



**Figure 12. Imagery captured by the VIPIR borescope camera during on-orbit operations.**

## V.  New Servicing Technology Center at NASA GSFC

A new robotic servicing development center is being established at NASA GSFC. Outfitting of the space is occurring during the summer and fall of 2015. Initial robotic test operations will begin in fall 2015. See Figure 13.

The center, which becomes operational in fall 2015, will host the following activities:
- Robot reach and access studies,
- Robot control algorithm validation,

- Space vision system testing,
- High speed computing system evaluations,
- Robotic tool design and prototype evaluation,
- Rendezvous and proximity operation sensor performance testing,
- On-orbit operations simulations with a remote control center,
- Space object autonomous capture testing,
- Refueling task demonstration,
- Spacecraft on-board video distribution and storage system testing,
- Situational awareness system testing,
- Astronauts working with robot mission simulations,
- Robot teleoperation testing,
- Propellant transfer system evaluations, and
- Servicing vehicle to client berthing system testing.

The center is divided into three workcells, A, B and C, each focusing on different aspects of in-space robotic applications.
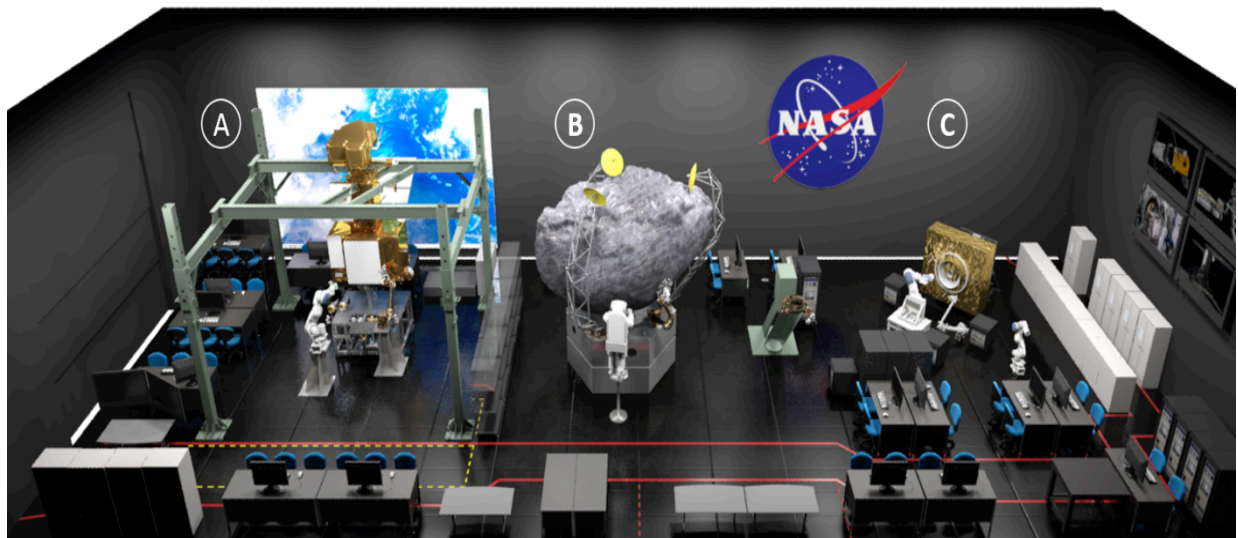


**Figure 13. The 'Cauldron,' a new robotic technology development center at NASA GSFC.**

### A. Workcell A – Series of Satellite Servicing Demonstration

Workcell A contains a full-size engineering model of the RSV payload module and a mock-up of representative client, Landsat 7. See Figure 13. The servicing payload has one operational seven degree-of-freedom (DOF) arm and one full size posable, seven DOF, robotic arm. The operational robot arm uses prototypes of an advanced tool drive system and tools to perform all of the tasks required to refuel a client spacecraft on orbit after berthing. Since the client spacecraft was not designed for servicing, several tasks need to be performed in order to gain access to the fueling port (FDV). These tasks include thermal blanket cutting and manipulation, safety wire cutting and safety cap removal. The RSV mock-up includes robot-mounted and situational awareness cameras. These will help determine what type of camera works best for teleoperations and also help determine optimal situational awareness camera placement.

This mock-up also accommodates propellant transfer demonstrations using a referee fluid. Propellant demonstrations require the robotic arm to mate with the FDV, establish a fluid seal, and open the valve to allow propellant transfer. The propellant transfer system will flow the referee fluid from the RSV payload to the mock client propellant tanks. Following successful propellant transfer, the robot arms and tool suite will closeout the valve worksite so the client could resume normal operations post-servicing. Inclusive to the payload testing is testing of other payload technologies such as video distribution and storage, and high-speed computing.

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This refueling task demonstration, from worksite access, refueling, and worksite closeout, mature SSCO capability and technology readiness for robotic servicing on orbit.

## B. Workcell B – Asteroid Redirect Mission

Workcell B focuses on testing elements of ARM, including segments from the ARRM and from the Asteroid Redirect Crewed Mission (ARCM). Workcell B consists of the ARV payload mockup. The ARV payload utilizes two robotic arms and capture tools to retrieve an asteroid from a larger asteroid surface. Additionally, three capture and restraint "legs" provide dual-function of spacecraft support during surface operations and asteroid restraint during ARV transit to lunar DRO. Upon arrival at lunar DRO, the ARCM mission will have astronauts performing extravehicular activities (EVAs) with the ARV to extract asteroid material samples.

Workcell B uses the ARV Payload mockup, primarily the robotic arms and legs, and a mock five-meter asteroid for development of the ARRM and ARCM missions. SSCO will investigate reach and access studies with the robot arms to determine capability and suitability of arm configurations in asteroid retrieval. The legs will simulate the restrained configuration of the asteroid. The relationships between the robotic arms and the legs will be evaluated and traded. In addition, the workcell will be used to simulate EVA activities with the ARV payload, utilizing the robotic arms and lander legs. These evaluations and studies will help build the appropriate configurations, technologies, techniques, and capabilities to successfully carry out the ARM mission.

## C. Workcell C – Autonomous Client Satellite Grasp

Grasping and berthing a satellite is vital to satellite servicing mission success.  Workcell C will mature and develop this crucial capability.  It contains a high-fidelity mockup of the aft-end of a notional client satellite, GOES-12. See Figure 13. The purpose of Workcell C is to mature capabilities required for the RSV to autonomously grasp a client, so that it can then be berthed for servicing. The workcell incorporates robotic arms equipped with an advanced tool drive, gripper tool, and vision technology so the robotic arms can autonomously align with and grasp a client satellite. The robot arms, tool drive, and tools use visual feature tracking algorithms, along with high-speed computing, to autonomously identify and track natural features on the aft end of a satellite. The pose estimate generated is used in closed-loop control to refine the gripper's position to ensure a successful grasp.

## VI.  Conclusion

NASA is maturing all the technologies required for successful in-space robotic operations, with ISS robotic experiments, EDU robot arm development, and near-term, dedicated robotic workcells for autonomous grasp, asteroid retrieval and satellite servicing. The Robotic Refueling Mission, active on ISS since 2011, continues with new and expanded task capability demonstrations. The NASA Servicing Arm, delivered to GFSC in June 2015, is under going full system integration and test with full operational status anticipated in the spring of 2016. Goddard's new servicing technology center, the 'Cauldron' facility, with its three workcells comes fully on line in fall 2015, with test operations in all workcells outlined for the next several years.

## Acknowledgments

## References

[1]NASA, "Request for Information: Space bus concepts to support the Asteroid Redirect Robotic Mission and In Space Robotic Servicing," 18 May 2015, URL: https://prod.nais.nasa.gov/eps/eps_data/165316-OTHER-001-001.pdf [cited 8 June 2015].

[2]Steitz, David. "NASA Announces Next Steps on Journey to Mars: Progress on Asteroid Initiative," 26 March 2015. URL: http://www.jpl.nasa.gov/news/news.php?feature=4523 [cited 8 June 2015].

[3]Rachel Kraft, "NASA's Refueling Demonstration Proves Viability of Satellite-Servicing Technologies," 8 Feb 2013, URL: http://www.nasa.gov/home/hqnews/2013/feb/HQ_13-046_RRM.html [cited 8 June 2015].